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THE THREE PRIMARY PARAMETERS OF IMAGING SYSTEMS AND DETECTIVE QUANTUM EFFICIENCY (D.Q.E.)

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ABSTRACT

A method of analyzing Imaging Sensors (independent of type of sensor, electro-optic (EO), photographic, infrared etc.) involving the concepts of Signal-to-Noise Ratio, Modulation Contrast, Resolution, Target Response Function (as related to Modulation Transfer Function (MTF)) and other system and operational parameters, is presented. Equations are derived for predicting resolution as a function of object-background modulation contrast, exposure (or irradiance), and wavelength, from Detector-Display Characteristic Curve, Optical Transfer Function (or Spread Function), RMS Noise Characteristics, Path Radiance, Veiling Glare, etc. Detection and Resolution Range equations are also derived. It is recommended that the approach outlined in this report be taken when comparing sensor systems of different types.

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ILLUSTRATIONS

LIST OF ABBREVIATIONS AND SYMBOLS

A	Area of resolution element
a	Area over which RMS measurements are made (noise integrated)
α	Angle subtended by a single bar of resolving power target
α_{LIM}	Limiting angular resolving power
B	Brightness
$\bar{B}$	Arithmetic mean brightness at display of target and background
B_M	Maximum Brightness
B_m	Minimum Brightness
CRT	Cathode Ray Tube
D	Diameter of lens aperature
D.Q.E.	Detective Quantum Efficiency
[DR]	Detection Range
E_T	Energy distribution of target
F	Effective focal length of lens
f#	f number = $\frac{D}{F}$
$\bar{g}_B$	Bar Gradient (Brightness) $\bar{g}_B = \frac{B_M - B_m}{H_M - H_m}$
g_B	Gradient as contrast approaches 0 - 1st Dirivitive
$\bar{g}_T$	Bar Gradient (Transmittance) $\bar{g}_T = \frac{T_M - T_m}{H_{dM}t - H_{dm}t}$
H	Irradiance
H_d	Irradiance on the Detector
$\bar{H}_d$	Arithmetic mean irradiance at detector of target background

$H_d t$	Exposure
$H_{dM} t$	Maximum Exposure
$H_{dm} t$	Minimum Exposure
H_M	Maximum Irradiance
H_m	Minimum Irradiance
H_S	Irradiance on the scene
k	S/N threshold
LED	Light Emitting Diode
λ	Wavelength of light
M	Modulation Contrast $M = \frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}}$
M_{in}	Modulation Contrast In
M_{OB}	Modulation Contrast of Object and Background
M_{ON}	Modulation Contrast on the Detector
M_{OUT}	Modulation Contrast out at the display $M_{OUT} = M_{WIN} \cdot \phi'_{\gamma}$
M_{WIN}	Modulation Contrast within the detector display subsystem $M_{WIN} = M_{OB} \cdot \phi_{S-\gamma}$
MTF/OTF	Modulation Transfer Function/Optical Transfer Function
$\overline{N}$	Arithmetic mean radiance between target and its background
N_A	Path Radiance
$\overline{N}_s$	Average Radiance over the whole scene
n	Number of Photons per Joule of radiant energy used
ϕ	Target Response Function $\phi = \frac{M_{out}}{M_{in}}$

$\phi_{D-\gamma}$	Target Response Function of detector/display subsystem less the gamma function
ϕ'_{γ}	Gamma Function Target Response Function due to film gamma not spatial frequency dependent
ϕ_L	Target Response Function of a Lens
ϕ'_{NA}	Target Response Function due to atmospheric backscatter (not spatial frequency dependent)
ϕ_O	Target Response Function of Optics
ϕ_S	Total (product of all) systems Target Response Function ϕ'_T times ϕ_T
$\phi_{S-\gamma}$	Total product of all Systems Target Response Functions except ϕ'_{γ}
ϕ_T	Total product of all Target Response Functions of all Spatial Frequency Dependent factors
ϕ'_T	Total product of all Target Response Functions of all Factors that are not Spatial Frequency Dependent
$\phi'_{T-\gamma}$	Total product of all Non-Spatial Frequency Dependent Target Response Functions except ϕ'_{γ}
ϕ'_V	Target Response Function due to Veiling Glare
$\hat{Q}$	Detective Quantum Efficiency as Contrast approaches zero
$\hat{Q}_M$	Detective Quantum Efficiency (D.Q.E.)
R	Resolution level
R_{LIM}	Resolution level limit or Resolving Power
[RR]	Recognition Range
ρ	Reflectance
$\bar{\rho}$	Arithmetic Mean Reflectance between Target and Background
$\bar{\rho}_S$	Average Reflectance over the whole scene
S	Size of object

S_S	Spread function of total system
S/N	Signal-to-noise Ratio
$(S/N)_{out}$	Signal-to-noise Ratio out usually measured at the display
σ_D	Granularity (rms fluctuation of density)
σ_T	rms fluctuation of transmittance
σ_B	rms fluctuation of brightness
$\sigma_{\overline{T}}^2$	1/2 the sum of the squares of maximum and minimum transmittance
T	Transmittance of transparency (image)
$\overline{T}$	Arithmetic Mean Transmittance between T_M and T_m
T_M	Maximum Transmittance of transparency
T_m	Minimum Transmittance of transparency
τ_A	Transmittance of the atmosphere
τ_L	Transmittance of optics and filter
τ_T	Total transmittance of system (atmosphere, optics, filter, etc.)
t	Time in seconds
V	Veiling glare (Mil Std 150)
V'	$= \frac{V}{1-V}$

SECTION I

INTRODUCTION

Image analysis procedures today are in a somewhat confused condition. Very few good standards and criteria exist. Many different concepts, and slight modifications, have resulted in a great many terms that have created semantic difficulties. Some of these terms and concepts are as follows:

(a) Dynamic Range
(b) Sensitivity
(c) Gamma
(d) Spread Function
(e) Modulation Transfer Function/Optical Transfer Function (MTF/OTF)
(f) Contrast
(g) Noise
(h) Signal to Noise Ratio
(i) Quantum Efficiency
(j) Detective Quantum Efficiency (D.Q.E.)
(k) Resolution or Resolving Power

The purpose of this report is to show the relationship that exists between the above concepts and how these concepts are related to the following three primary parameters:

(a) Detector-Display Characteristic Curve
(b) Systems Target Response Function
(c) Systems Noise Characteristics

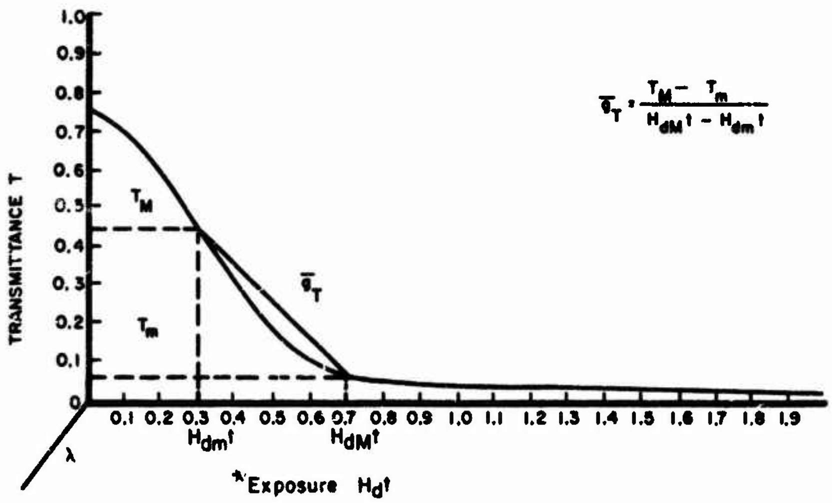
It will also be shown how these three parameters can be applied to the complete analysis of any imaging system which utilizes incoherent radiation from UV through the IR either electro-optical or photographic.

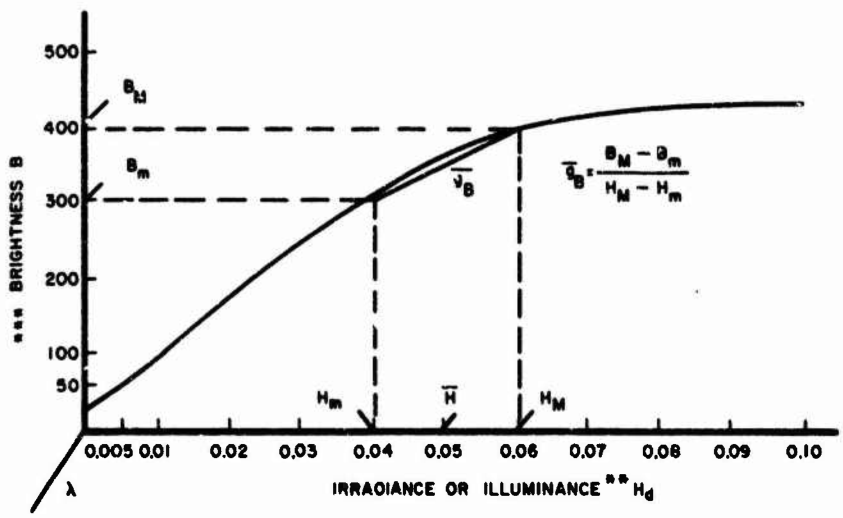
SECTION II

DETECTOR-DISPLAY CHARACTERISTIC CURVE

Perhaps the most significant parameter, or at least historically the oldest, is the "Characteristic Curve" sometimes referred to (when plotted on log coordinates) as the H and D or D/Log E curve. This parameter is a plot of input at the detector (either power or energy per unit area) and output at the display. It is best shown as in Figure 1, in which two types of Detector/Display Characteristic Curves are shown. Figure 1a is representative of systems wherein there is a "hard copy" display or an output that produces a variation in brightness (with no time dependent noise) as a result of spatially varying reflection, scattering, or transmission of ambient or incident illumination. Photographic type outputs such as silver halide negatives, transparencies, or prints as well as the newer unconventional photo process are included. The input axis in this case is the "exposure" (product of irradiance or illuminance [on the detector] and exposure time or integration time) in units of energy per unit area incedent on the detector. In the case of direct (negative or reversal) photo processes the "detector" also becomes (after processing) the display. This need not always be true as, for example, electro-optical and infrared scanning systems in which the input can be on one of several types of detectors and the output is a "hard copy". In either case transmittance (or reflectance) is plotted as a function of exposure on the detector in a linear plot. In this case, the exposure time (or integration time) can be determined, at the detector, at the recording plane, or a combination of both. Integration time t is the length of time over which photons are "counted" at the detector. It is relative to dwell-time in scanning systems and to time constant in some AC coupled systems.

The other curve, Figure 1b, is representative of those systems which produce, as an output, a display which is a spatial pattern of brightness or radiance and this brightness is a time dependent function of the irradiance or illumination on the detector. T.V. direct view image converters and intensifiers are typical of this type of system.





* H_dt Can Be In Either Radiometric Or Photometric Units. In This Case It Is Meter Candle Seconds (MCS)

**H_d Can Be in Either Radiometric Or Photometric Units In This Case It Is In Foot Candles.

***B B Can Be In Either Radiomet-ic Or Photometric Units. In This Case It Is In Foot Lamberts.

Figure 1. Detector-Display Characteristic Curves

In this case, output in units of "brightness" either luminance (ft lamberts) or radiance (watts per sq meter per steradian) are plotted as a function of irradiance or illumination on the detector. This too is best shown as a linear plot. Both of these curves are really three dimensional plots with wavelength (λ) plotted on the third axis. From practical considerations, however, the data is most often given for one specified type of radiation (with a specified spectral distribution) for example--daylight, white light, tungsten (or other material at a specified temperature) any of these with a specified filter or black body radiation of a specified "color" temperature.

In addition to specifying the spectral nature of the irradiation on the detector it is also necessary to specify all the important conditions which are applicable to the particular data. The following types of information are important in photo-like processes:

Film type and emulsion number
Age and condition of film
Type of illumination and optical filter
Temperature (at exposure plane)
Exposure time
Developer
Development time and temperature
Type of agitation
Type of developer and/or other processing solutions

Any change in any of the above will have a measurable effect on the Characteristic Curve. In addition, when the system between detector and "hard copy" or dynamic display includes electronic or electro-optical components the following types of parameters must likewise be specified:

Detector type and description
Temperature of detector at time of exposure
Operating conditions of detector/voltage bias, etc.
Amplifier's gain settings

Nature or description of electronic filters

Type of irradiance used for photo exposure (glow tube, cathode ray tube (CRT), light emitting diodes (LED), etc.)

Display phosphor characteristics

Operational setting of display subsystem

Degree of exposure redundancy (how many "frames" are exposed or actual photo exposure time)

These detector/display characteristic curves can be used to determine a, b and c in the first paragraph of the introduction. These concepts of dynamic range input at the detector, sensitivity and gamma, are very important in determining the suitability of a system as it is applied against a particular scene. Dynamic range (output at the display) is an important measure of image quality (the higher the better).

SECTION III

SYSTEMS TARGET RESPONSE FUNCTION

This parameter is related to, but should not be confused with, MTF/OTF (see Figure 2a). The Systems Target Response Function is spatial frequency dependent and includes the effect of the spread function or its Fourier Transform (MTF/OTF). It is also, however, a function of the type of target being considered and includes those contrast (modulation) reducing factors which are not spatial frequency dependent (see Figure 2b), such as atmospheric backscatter, internal system optical scattering (veiling glare), and internal radiation. In Figures 2a and 2b we show the two types of contrast (modulation) reducing functions and a typical MTF. The function ϕ is defined as

$$\phi \equiv \frac{M_{OUT}}{M_{IN}}$$

and is plotted as a function of spatial frequency (usually measured at the detector). Figure 3 shows how, for different types of targets, ϕ_L varies as a function of spatial frequency (Reference 1). If the target under consideration is a single bar or spot then it is more convenient to plot ϕ as a function of target size (Reference 1) (see Figure 4) (again usually referenced to the detector plane). When the target is a sinusoidally varying target ϕ becomes the MTF or Fourier transform of the system spread function. Figures 3 and 4 were computed assuming a diffraction limited spread function (Bessel function). Note that ϕ for a single bar or spot is also a function of the modulation of the target and its background. It is also greatly dependent on whether the bar or spot is lighter than the background or darker than the background. This is one reason why bright objects are easier to detect than dark objects even when the arithmetic mean radiance between target and background remains the same. This is not true when "resolving" multi-bar targets.

As illustrated in Figure 2b there is a contrast (modulation) reducing property of optical systems which is not dependent on the spatial

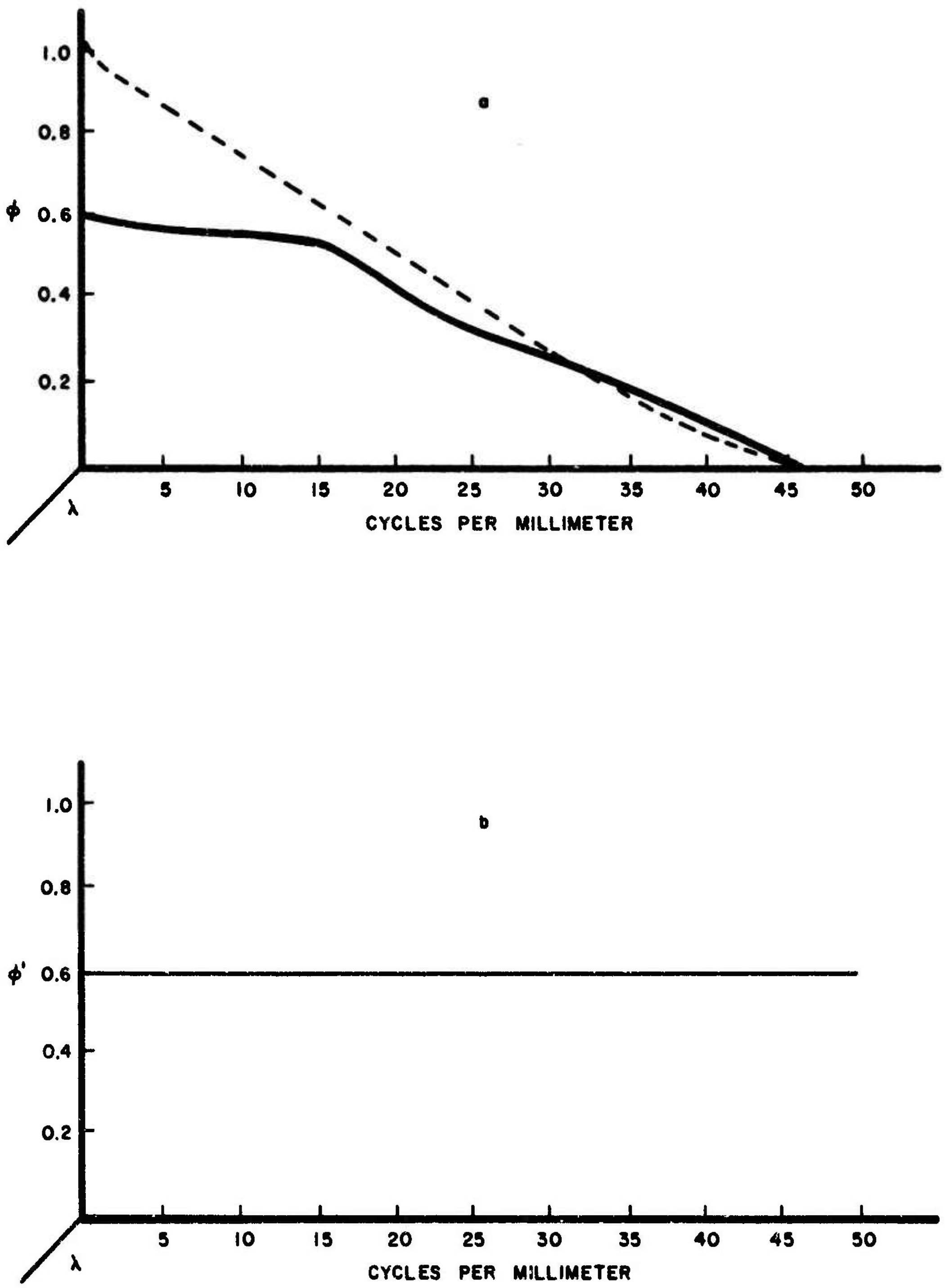


Figure 2. Target Response Function

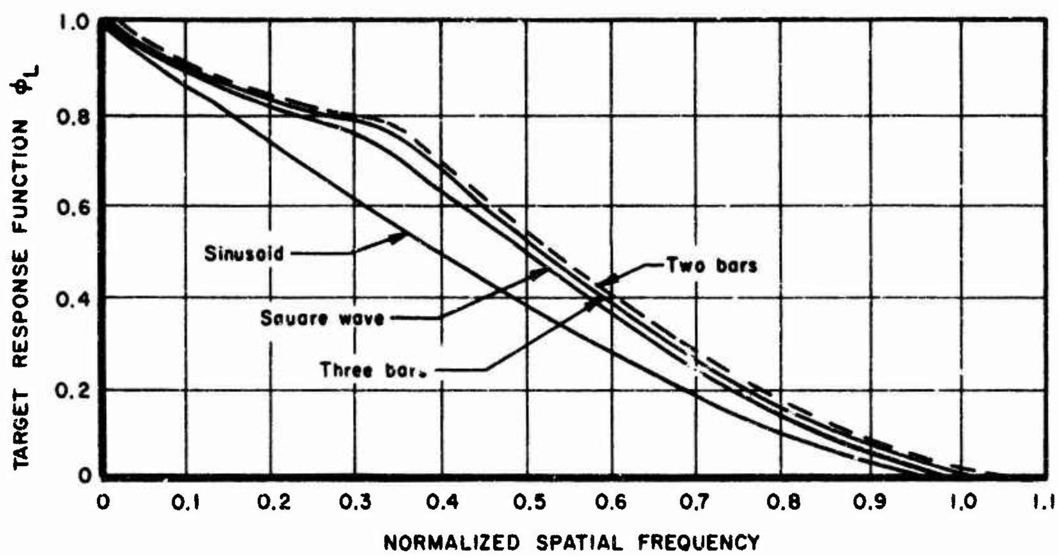


Figure 3. Various Target Response Functions ϕ_L for a Perfect Diffraction Limited Lens

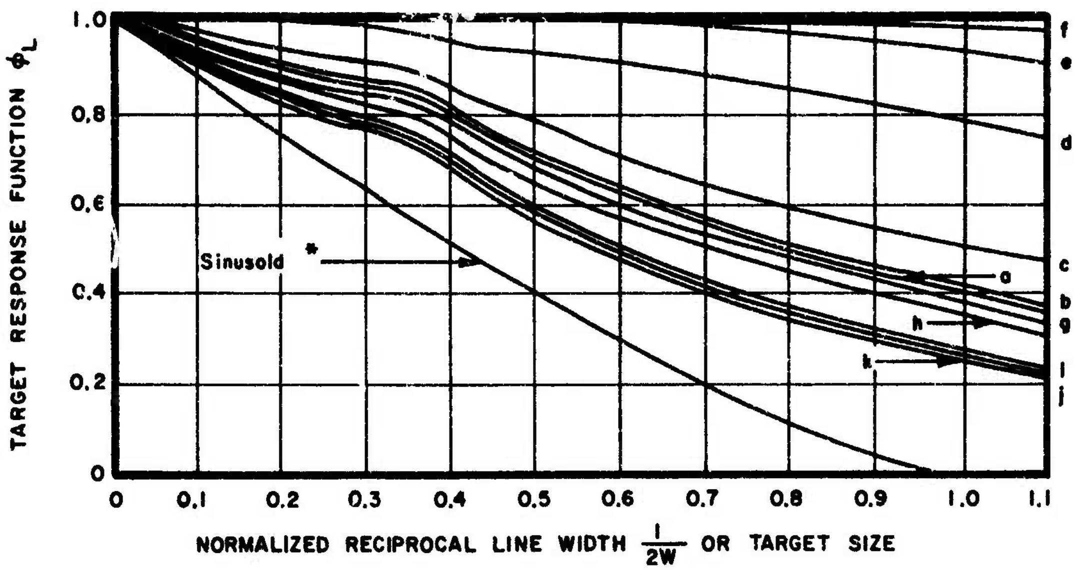


Figure 4. Single-Bar Target Response Function ϕ_L for a Perfect Diffraction Limited Lens

a RELATIVE AMPLITUDE AS A FUNCTION OF $\frac{1}{2W}$

b M_{OB} = .05 Line Brighter Than Background

c " = .33 "

d " = .82 "

e " = .98 "

f " = .99 "

g M_{OB} = .05 Line Darker Than Background

h " = .33 "

i " = .82 "

j " = .98 "

k " = .99 "

frequency or type of target. Two typical causes of this type of contrast (modulation) reduction is atmospheric backscatter and veiling glare. In the case where the scene is illuminated by a distant source of energy (sun, sky, moon, stars, etc.) and when the backscatter can be determined in terms of path radiance (Reference 2):

$$\phi'_{NA} = \frac{1}{1 + \frac{N_A}{\overline{N}\tau_A}} \tag{1}$$

where ϕ'_{NA} = Response function due to atmospheric backscatter [the prime indicates that it is not spatial frequency or target dependent].

N_A = Path radiance [this is a function of average scene reflectance and atmospheric conditions].

$\overline{N}$ = Arithmetic mean radiance between target and its background

τ_A = Transmittance of the atmosphere

Measurements of the ratio $\frac{N_A}{\overline{N}\tau_A}$ have indicated values ranging from close to 0 to, under some conditions, greater than 30. Therefore, ϕ'_{NA} can often be as low as .03 or the contrast (modulation) at the sensor can be .03 of what it is at the target.

For the case of veiling glare, where V is defined as veiling glare in accordance with MIL-STD-150, it is useful to use V' where

$$V' = \frac{V}{1 - V} \tag{2}$$

then

$$\phi'_V = \frac{1}{1 + \frac{V'\overline{\rho}_S}{\overline{\rho}}} \tag{3}$$

where ρ_S = average reflectance over the whole scene

$\bar{\rho}$ = average (arithmetic mean) reflectance between the target and its background

It can also be shown that

$$\phi'_V = \frac{1}{1 + \frac{V'\bar{N}_S}{\bar{N}}} \tag{4}$$

where $\bar{N}_S$ = average Radiance over the whole scene

$\bar{N}$ = average (arithmetic mean) Radiance between the target and its background

Another useful expression is the "Gamma Function" *which is also not spatial frequency dependent.

$$\phi'_\gamma = \frac{\bar{g}_B \bar{H}_d}{\bar{B}} \tag{5}$$

where $\bar{g}_B$ = the slope of the characteristic curve between two points on the curve determined by $\bar{H}_d$ and the contrast (modulation).

$\bar{H}_d$ = Arithmetic mean irradiance at the detector of target and background (see Figure 1b)

$\bar{B}$ = Arithmetic mean brightness at the display, of target and background (see Figure 1b)

This function ϕ'_γ is independent of the units used to define the characteristic curve in Figures 1a and b. One can easily see that for all systems over the full dynamic range there is no single value for ϕ'_γ. Except over the linear portion of the Characteristic Curve, and most

*Not to be confused with the mathematical concept also called gamma function.

systems are not linear, ϕ'_γ is a function of the level of irradiance and the contrast (modulation) under consideration. One useful device is to treat systems evaluation in terms of very low contrast, i.e., let $M \to 0$ then for $\bar{g}_B$ we can use the first derivative of the characteristic curve, and:

$$\phi'_\gamma = \frac{\dot{g}_B \; H_d}{B} \quad \text{when } M \rightarrow 0 \tag{6}$$

One can also treat the case of "hard copy" processes in a similar manner and

$$\phi'_\gamma = \frac{\bar{g}_T \, \bar{H}_d t}{\bar{T}} \tag{7}$$

where $\bar{g}_T$ = the slope of the characteristic curve between two points on the curve determined by $\bar{H}_d t$ and the contrast (modulation).

$\bar{H}_d t$ = Arithmetic mean exposure, at the detector, of target and background. (see Figure 1a)

$\bar{T}$ = Arithmetic mean transmittance (or reflectance) [of the "hard copy" (film or print)] of target and background. (see Figure 1a)

To determine the total nonspatial frequency dependent-target response function one can multiply

$$\phi'_T = \phi'_{NA} \cdot \phi_V \cdots \phi'_\gamma \tag{8}$$

For infrared systems one could fefine a term ϕ'_R to account for internal radiation sources.

While it is possible to define ϕ (the spatial frequency dependent part of the target response function) for each component of the system such as optics (including the atmosphere, lenses, mirrors, filters, etc.) detectors (including film, point detectors, mosaics, etc.) electronics, scanning operation, display, etc., it is not proper to obtain the total ϕ_T by multiplying all these individual functions. This can, only be done when the target under consideration is a sinusoidal target. ϕ_T is determined by convoluting all the spread functions with the target under

consideration. For sinusoidal targets ϕ_T is the MTF or the fourier transform of the total spread function. It is also the product of the individual MTFs. For nonsine targets, with which we are most concerned, ϕ is obtained by convoluting the spread function with the target under consideration and computing the resulting contrast (modulation). The modulation out is then divided by the modulation in to determine ϕ. This is repeated at several spatial frequencies. The spread functions can be measured directly, calculated, or obtained by taking the inverse Fourier transform of the MTF. ϕ_T, therefore, can only be obtained from the total spread function. Once we have ϕ_T and ϕ'_T the combined target response function of the total system ϕ_S (both nonspatial frequency dependent and spatial frequency dependent terms) is

$$\phi_S = \phi'_T \cdot \phi_T$$

Another useful concept is the systems target response function less the gamma function, thus:

$$\phi_{S-\gamma} = \phi_T \; \phi'_{T-\gamma} = \phi_T \cdot \phi'_{NA} \cdot \phi'_V \cdots \phi'_R \qquad (9)$$

This concept enables one to handle nonlinear systems in a convenient manner. From the above discussion it follows that:

$$M_{WIN} = M_{OB} \cdot \phi_{S-\gamma} \qquad (10)$$

$$M_{OUT} = M_{WIN} \cdot \phi'_\gamma \qquad (11)$$

where

M_{WIN} = Contrast (Modulation) "within" the detector/display portion of the system. This includes all target response functions except the gamma function.

M_{OB} = Contrast (Modulation) of the object (target) and background, at the object or target.

Likewise

$$M_{ON} = M_{OB} \cdot \phi_O \cdot \phi'_{T-\gamma} \qquad (12)$$

where

M_{ON} = Contrast (Modulation) on the detector

ϕ_O = Target response function of optics

$\phi'_{T-\gamma}$ = Target response function (nonspatial frequency dependent less ϕ'_{γ}

$$M_{WIN} = M_{ON}\ \phi_{D-\gamma} \tag{13}$$

where

$\phi_{D-\gamma}$ = Target response function of detector/display subsystem less the gamma function.

The above discussion is vital to the proper understanding of how spread function, MTF, and contrast, (d, e and f on page 1) are involved in system analysis procedures.

SECTION IV

SYSTEMS NOISE CHARACTERISTICS

Noise in images is defined as the RMS fluctuation in the brightness (of a dynamic display) or transmission (granularity of a static display). This rms variation can be caused by numerous physical processes (References 3, 4 and 5). It is not the purpose of this paper to discuss the sources of this noise. All sources of noise should be combined into one measurement. This measurement should be made at the output or display and is called "noise out". Since the nature of this noise is statistical (involving a fairly large sample of events*) the value (expressed as σ_T or σ_B; see Figures 5a and b) is dependent on the size of the area over which the noise is measured and (in the case of dynamic noise, Figure 5b) the length of time over which the noise is integrated (measured). It is, therefore, absolutely necessary to specify the size (diameter or area) of measuring aperture and, in the case of dynamic displays, the integration time. For static displays within the spot size limits over which we are concerned it can be shown that for a specific sample:

$$\sigma_T \sqrt{a} = \text{A constant} \tag{14}$$

where

σ_T = RMS fluctuation of transmittance

a = Area over which measurement was made (integrated)

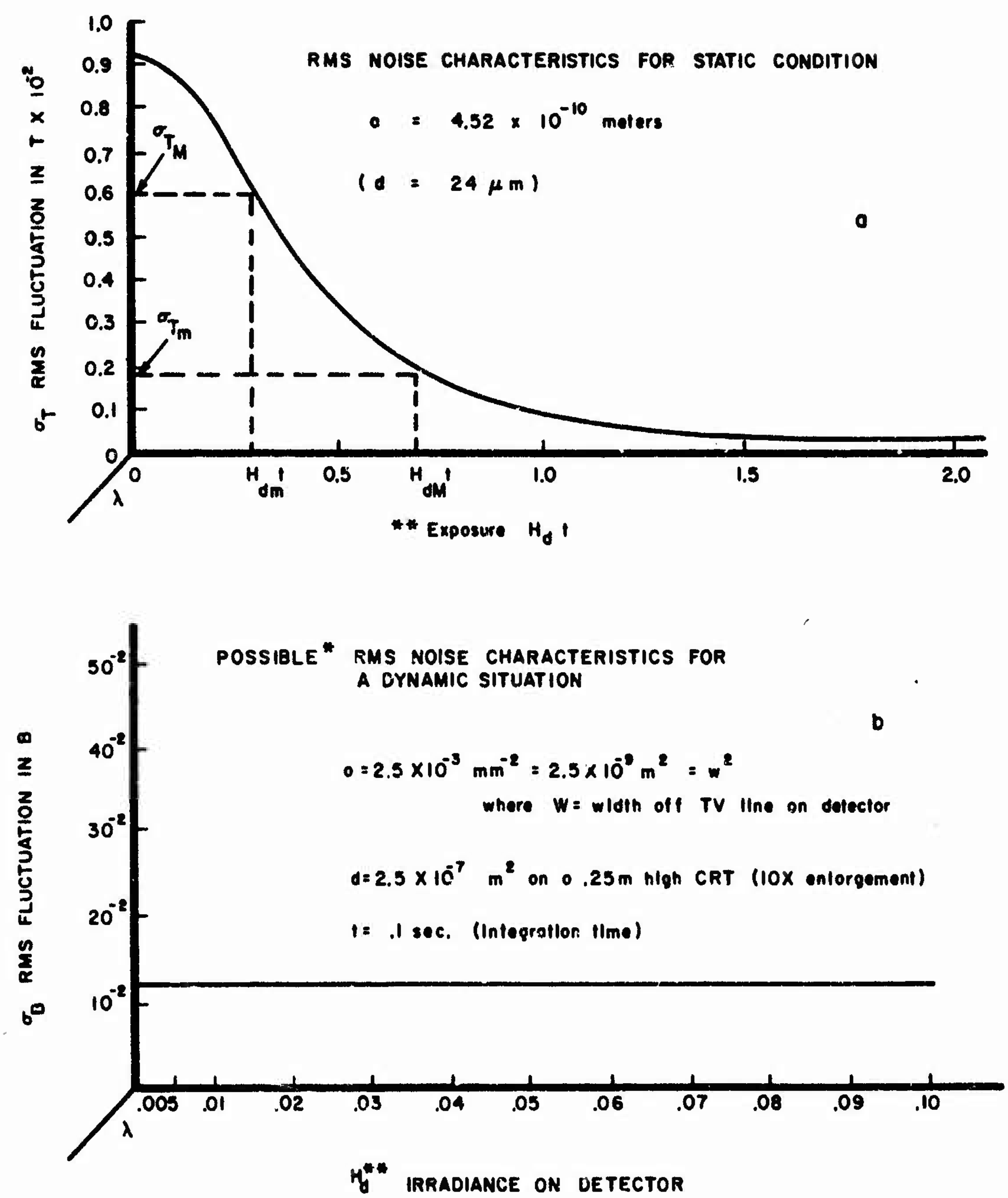
This is another form of Selwyn's law (Reference 6) and holds except when a is comparable in size to the area of individual photographic grains. Likewise, it can be shown that:

$$\sigma_B \sqrt{a\,t} = \text{A constant} \tag{15}$$

where t is the integration time.

Measurements of photo materials and electro optical systems have shown that σ_T or σ_B is often a function of the level of irradiance on the detector.

*These events are either flashes of light, small spots of light or photographic grains.



*This Case Is Said To Be System Noise Limited When "Photon Noise" Is Very Small Compared With Other Noise. Here RMS Noise Is Not A Function Of Level Of Irradiance On The Detector. This Data Is Approximate Only. Good C.R.T. Data Not Available.

**See Notes On Figure 1

Figure 5. System Noise Characteristics

Figure 5a shows the most convenient way of plotting this information for a photo like system producing a "hard copy". Figure 5b shows data for a dynamic type display in which the noise source (could be a poor amplifier in the circuit) is not a function of the level of irradiance (illumination) on the detector. In both cases the area over which the measurements are made must be given. In Figure 5b one must also specify the applicable integration time. The other conditions under which the measurements are made, as shown in Section II, must also be given.

Signal to Noise ratio from the display is a more useful term than just noise; it is defined as:

$$(S/N)_{OUT} = \frac{T_M - T_m}{\left(\sigma^2_{T_M} + \sigma^2_{T_m}\right)^{1/2}} \qquad (16)$$

or

$$(S/N)_{OUT} = \frac{B_M - B_m}{\left(\sigma^2_{B_M} + \sigma^2_{B_m}\right)^{1/2}} \qquad (17)$$

where

T_M = Transmission of target or background whichever is greater

T_m = Transmission of target or background whichever is less

σ_{T_M} = RMS fluctuation in T_M over integration area a

σ_{T_m} = RMS fluctuation in T_m over integration area a

B_M = Brightness of target or background whichever is greater

B_m = Brightness of target or background whichever is less

σ_{B_M} = RMS fluctuation in B_M over integration area a and integration Time t_1

σ_{B_m} = RMS fluctuation in B_m over integration area a and integration Time t_1

A review of the above and Figures 1 and 5 will show that $(S/N)_{out}$ is a function of the level of irradiance on the detector, the contrast (modulation) within the detector display, the size of the target under consideration and the integration time.

Rose (Reference 7) and others (References 4 through 10) have shown that a useful concept in evaluating imaging systems is Detective Quantum Efficiency written as D.Q.E. or sometimes $\hat{Q}$. In this paper we use $\hat{Q}_M$ to indicate that this method of evaluating $\hat{Q}$ makes it dependent on M (contrast) in nonlinear systems. As M approaches 0 this method of determining Q results in the same values as others have used for the low contrast case. Detective Quantum Efficiency is defined as:

$$Q_M = \frac{(S/N)^2_{out}}{(S/N)^2_{in}} \tag{18}$$

$(S/N)_{in}$ is computed on the basis of considering only the so called photon fluctuation.

$(S/N)_{in}$ is equal to

$$\frac{N_M - N_m}{(N_M + N_m)^{1/2}} \tag{19}$$

when N_M is the number of photons from a small area of target or background whichever is larger. N_m is the number of photons from same size area of target or background whichever is smaller. This is based on the well known assumption that photon statistics (or photon detector interaction) is Poisson thus RMS fluctuation equals the square root of the mean. This definition of S/N implies both spatial and temporal integration.

It can be shown that D.Q.E. can be calculated from the characteristic curve (Figures 1a and b) and the noise characteristic (Figures 5a and b).

Two types of relationship involving these curves are used dependent upon whether the noise is "dynamic" or "static". For the static case:

$$\hat{Q}_M = \frac{2\bar{g}_T^2 \bar{H}_d t}{\left(\sigma_{T_M}^2 + \sigma_{T_m}^2\right) a n} = \frac{\bar{g}_T^2 \bar{H}_d t}{\bar{\sigma}_T^2 a n} \qquad (20)$$

where

$\hat{Q}_M$ = Detective Quantum Efficiency (using modulation contrast)

$\bar{g}_T$ = Slope between two points (representing max and min exposure for a specified modulation contrast) on the transmission vs Exposure curve

$\bar{H}_d t$ = Arithmetic mean exposure, in joules per sq meter, between max and min exposure for a specified modulation contrast.

σ_{T_M} = rms variation in transmittance (of picture) for max transmittance value

σ_{T_m} = rms variation in transmittance (of picture) for min transmittance value

a = Area of aperture in square meters used to measure σ_{T_M} and σ_{T_m}

$\bar{\sigma}_T^2$ = 1/2 the sum of the squares of max and min rms transmittance

n = Number of photons per joule for quality of light used in exposure

for the case where the noise is dynamic

$$\hat{Q}_M = \frac{\bar{g}_B^2 \bar{H}_d}{\bar{\sigma}_B^2 a t n} \qquad (21)$$

where

$\hat{Q}_M$ = Detective Quantum Efficiency (using modulation contrast)

$\bar{g}_B$ = Slope between two points (representing max and min irradiance for a specified modulation contrast) on the Brightness vs Irradiance curve

$\bar{H}_d$ = Arithmetic mean irradiance at detector in watts per square meter.

$\bar{\sigma}_B{}^2$ = 1/2 the sum of the squares of max and min rms brightness

a = Area of aperture in meters used to measure σ_{B_M} and σ_{B_M}

n = Number of photons per joule for quality of light used.

This definition of D.Q.E., it will be noted, includes all possible sources of noise since the noise is measured at the output of the display. Equations (20) and (21) reduce to other well known methods for determining D.Q.E. as the contrast (modulation) approaches 0. The term "Quantum Efficiency" (Reference 4) is often applied to a detector and defined in terms of the ratio of photo-electrons out to photons incedent on the detector. D.Q.E. of a system (which includes all sources of noise) would be equal to the Quantum Efficiency of the detector only if there were no other sources of noise than the so called "photon noise" or "recombination noise". This discussion, involving Figures 5a and b, noise, signal-to-noise ratio, Quantum Efficiency and Detertive Quantum Efficiency explains important aspects of items g, h, i, j in the introduction. To relate all the concepts in the introduction we next consider resolution.

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13. ABSTRACT

A method of analyzing Imaging Sensors (independent of type of sensor, electro-optic (EO), photographic, infrared etc.) involving the concepts of Signal-to-Noise Ratio, Modulation Contrast, Resolution, Target Response Function (as related to Modulation Transfer Function (MTF)) and other system and operational parameters, is presented. Equations are derived for predicting resolution as a function of object-background modulation contrast, exposure (or irradiance), and wavelength, from Detector-Display Characteristic Curve, Optical Transfer Function (or Spread Function), RMS Noise Characteristics, Path Radiance, Veiling Glare, etc. Detection and Resolution Range equations are also derived. It is recommended that the approach outlined in this report be taken when comparing sensor systems of different types.

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Spread Function						
Noise						
Resolution						
Resolving Power						
Detector						
Display						
Characteristic Curve						
Veiling Glare						
Contrast						
Modulation Contrast						
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Recognition Range						
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THE THREE PRIMARY PARAMETERS OF IMAGING SYSTEMS AND DETECTIVE QUANTUM EFFICIENCY (D.Q.E.)

PAUL L. PRYOR

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AFAL-TR-73-37

FOREWORD

This report was prepared by the Reconnaissance Applications Branch, Reconnaissance and Surveillance Division, Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio. This study was part of an in-house work unit under Project 7645 "Aerospaceborne Reconnaissance Subsystem Development", Task 76450816, entitled "A General Approach to Image Analysis". The work was performed by Mr. Paul L. Pryor (AFAL/RSA), Senior Scientist during the period of January 1970 through January 1972. Some computer calculations were made by Data Corporation to prove out the prediction of resolving power threshold modulation detectability curves. Some special computer programs were developed and used by Data Corporation in 1971 for this purpose.

Two talks were given by the author covering much of the material in this report. One was given at the International Conference on Electro-Optical Systems Design at Brighton, England on 1 March 1972. The other talk was given to the Society of Photographic Scientists and Engineers at San Francisco, California, on 10 May 1972.

This report was submitted by the author in June 1972.

This technical report has been reviewed and is approved.

D Roger Sink

D. ROGER SINK, Acting Chief
Reconnaissance Applications Branch
Reconnaissance/Surveillance Div
AF Avionics Laboratory

SECTION V

RESOLUTION

The concept of resolution, which has often been used loosely (item k, page 1), is related to spatial frequency (see Figure 2). It can in a two dimensional image be thought of as an area, i.e., the resolution element A (where $A = \frac{1}{4R^2}$ and R = spatial frequency). For any given resolution element, i.e., small area, there is (at the display a $(S/N)_{out}$; the larger the area the greater is this S/N. This $(S/N)_{out}$ is also dependent on the contrast (modulation) in or "within" the detector display (see Section IV). This interdependent relationship is quite simple and is shown with the following equation:

$$\frac{R^2 (S/N)^2_{OUT}}{M^2_{WIN}} = \frac{H_d \, t \, n \, \hat{Q}_M \times 10^{-6}}{2} \qquad (22)$$

where

R = Resolution level in line pairs per mm at the detector. R^2 is inversely proportional to $A = \frac{1}{4R^2}$ the area of a resolution element (or cell) at the detector over which $(S/N)_{out}$ is determined for a given M_{win} (or vice versa.)

$(S/N)_{out}$ = Signal-to-Noise Out at resolution level R for M_{win}

M_{win} = Contrast within the detector/display subsystem (defined as modulation $\frac{Max-Min}{Max+Min}$)

$\overline{H}_d$ = Average Irradiance (arithmetic mean) in watts per square meter on the detector, of target and background

t = Integration time in seconds over which photons are counted

$\hat{Q}_M$ = D.Q.E. (Detective Quantum Efficiency) = $\frac{(S/N)^2_{out}}{(S/N)^2_{in}}$

n = Number of Photons per joule for the spectral quality of the light used over the applicable spectral interval.

As the resolution R is increased the $(S/N)_{out}$ decreases until it reaches a threshold at which the probability of the discriminator (usually the eye/mind combination) to resolve the target, is low (approximately 50%). This limit is called the limiting resolution (R_{LIM}) and is usually what is meant by resolving power. Considerable effort has recently been expended on determining the S/N threshold (References 3 and 10) with psycho-physical experiments. When this S/N threshold (k) is referred to the area of a single resolution element, and not the total area of the bar in a multi-bar or long single line target, it has been found that it is dependent on the aspect ratio of the line. k is also a function of whether the noise is static or dynamic as well as other conditions such as angle subtended by the target at the eye. In the case of static noise and a three bar target 5:1 aspect ratio (photography) k = 1.61 has been used (Reference 3) successfully and for the case of dynamic noise k = 1.2 has also been used for a three bar 5:1 aspect ratio target. In the case of detecting the presence (with dynamic noise sensors) of a single isolated spot the S/N threshold (Reference 10) is approximately 3.

If one substitutes R_{LIM} (resolving power or resolution limit) for R and k (signal to noise threshold) for $(S/N)_{out}$ in Equation (22) the following relationship results:

$$R_{LIM} = \frac{M_{WIN}\left(\overline{H}_d \, t \, n \, \hat{Q}_M\right)^{1/2} \times 10^{-3}}{1.414\ k} \tag{23}$$

or from Equation (10)

$$R_{LIM} = \frac{M_{OB}\ \psi_{S-\gamma}\left(\overline{H}_d \, t \, n \, \hat{Q}_M\right)^{1/2} \times 10^{-3}}{1.414\ k} \tag{24}$$

It can be shown that H_d can be expressed as

$$\overline{H}_d = \frac{\overline{\rho}\, H_S\, \tau_T + N_A \pi \tau_L + V' \overline{\rho}_S\, \tau_T + V' N_A \pi \tau_L}{4f\#^2} \tag{25}$$

where

$\overline{H}_d$	=	Arithmetic mean irradiance on the detector in watts per m^2 of object (target) and background
$\overline{\rho}$	=	Arithmetic mean reflectance of object and background
H_S	=	Irradiance on the scene in watts per m^2
τ_T	=	Total transmittance of system (atmosphere, optics filter, etc.)
N_A	=	Path radiance in watts per m^2 per steradian
τ_L	=	Transmittance of optics and filter
V'	=	Veiling glare of sensor
$\overline{\rho}_S$	=	Average scene reflectivity

This equation reduces to the well known expression (neglecting magnification and off axis variation in illumination) of

$$\overline{H}_d = \frac{\overline{\rho}\; H_S}{4f\#^2} \quad \text{when } N_A \text{ and } V' = 0 \tag{26}$$

By substituting this expression into Equation (24) we obtain

$$R_{LIM} = \frac{M_{OB}\; \phi_{S-\gamma}\; (\overline{\rho}\, H_S\, \tau_T\, t\, n\, \hat{Q}_M)^{1/2} \times 10^{-3}}{2f\#\, 1.414\, k} \tag{27}$$

If we let α be the angle subtended by a single bar (not a bar and a space) then limiting angular resolution or angular resolving power

$$\alpha_{LIM} = \frac{1}{2\, R_{LIM}\, F} \tag{28}$$

Where F = effective focal length of optical system with α expressed in radians and F (focal length) expressed in millimeters. Substituting Equation (28) into Equation (27) we obtain

$$\alpha_{LIM} = \frac{k\ 1.414 \times 10^3}{M_{OB}\ \phi_{S-\gamma} \left(\bar{\rho}\ H_S \tau_T\ t\ n\ \hat{Q}_M\right)^{1/2} D} \tag{29}$$

where

α_{LIM}	=	Limiting angular resolution (resolving power) in milli radians. (α = angle subtended by one line of a resolving power target: not a line pair)
k	=	S/N threshold
M_{OB}	=	Contrast (modulation) of object (target) and its background
$\phi_{S-\gamma}$	=	Target response function for total system less the "gamma function"
$\bar{\rho}$	=	Arithmetic mean reflectivity of object (target) and its background
H_S	=	Irradiance on scene in watts per square meter
τ_T	=	Total transmittance of system from object to detector
t	=	Integration time in second
n	=	Number of photons per joule of radiant energy used
$\hat{Q}_M$	=	Detective Quantum Efficiency
D	=	Diameter of optical collector in meters

This reduces to the well known Rose equation (Reference 7) when we assume $\phi_{S-\gamma} = 1$, $\tau_T = 1$, $\gamma = 1$, that the contrast is expressed as percent contrast instead of modulation contrast, that photometric units are used instead of radiometric units and that $\bar{\rho}\ H_S$ is expressed as

"brightness" B. n is combined with the numberical constant and thus

$$B\,a^2 M_{OB}^2 = \frac{k^2\ 2 \times 10^6}{tQD^2\ \ n} \tag{30}$$

By substituting Equation (20) into Equation (24) one obtains

$$R_{LIM} = \frac{M_{OB}\,\phi_{S-\gamma}\,\overline{H}_d\,t\,\overline{q}_T \times 10^{-3}}{k\ \overline{\sigma}_T\ \sqrt{a}\ \ 1.414} \tag{31}$$

where

R_{LIM}	=	Limiting Resolution (resolving power) in line pairs per mm at the detector
M_{OB}	=	Contrast (modulation) of object (target) and its background
$\phi_{S}-\gamma$	=	Target response function for total system less the "gamma function"
$\overline{H}_d t$	=	Arithmetic mean exposure at the detector
$\overline{q}_T$	=	Slope between appropriate points in Characteristic curve [see Equation (20) and Figure (1)]
k	=	S/N threshold
$\overline{\sigma}_T$	=	the square root of 1/2 the sum of the squares of max and min RMS transmission [see equation (20) and Figure (5)]
a	=	Area of spot (in m^2) over which RMS noise is integrated

This equation was tested against measured data in the following manner. Perkin-Elmer (P-E) resolving power measurements on E. K. film #3404 were compared with data computed with the above equation. M_{OB} (target to background modulation contrast) was available for the Perkin-Elmer resclving power measurements. The MTF of "diffraction limited" microscope lens was combined with the MTF of the film (see Figure 6). Note that accurate data on film MTF is nonexistent. Curve C was finally used since this agrees better with what we would expect the MTF to be if one could ignore the grain structure in the film when

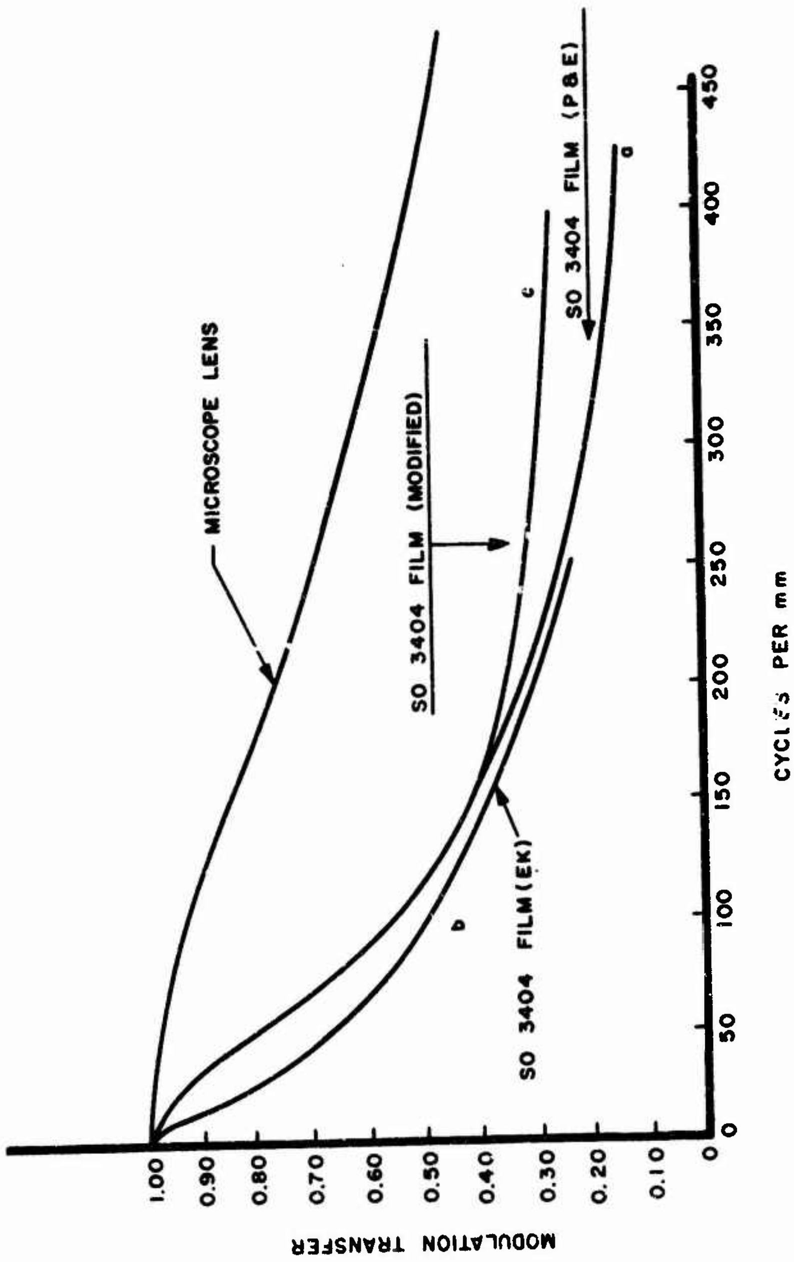

Figure 6. Modulation Transfer Function Data

making measurements. Actually this curve agrees very well with hypothetical data published by Eastman Kodak researchers (Reference 11). No other contrast (modulation) reducing factors were assumed to exist since the measurements were made in a carefully controlled laboratory environment. Photometric units were used for H_d since the units of $\bar{g}_T$ involve these units also--no problem arose. The data for determining $\bar{g}_T$ and σ_T were obtained from P-E in the form of H and D curves (D Log E) and σ_D vs D curves. These curves were converted to Transmittance vs exposure and σ_T vs exposure with correction for the Callier coefficient and the viewing lens used in reading the resolving power. k = 1.61 was used. Figure 7 shows the measured and calculated values of resolving power as a function of exposure. In a similar manner the measured and calculated threshold detection curves were computed and compared to one determined by P and E (see Figure 8).

The same type of analysis can be applied to electro-optical systems such as Television, Direct View Image Intensifier, Raster Scan Infra red sensors, Line Scan Infra red sensors, etc. The data, however, to make this analysis, to my knowledge, does not exist. It appears that no one is making careful brightness and rms variation in brightness measurements off the face of the display where it really matters.

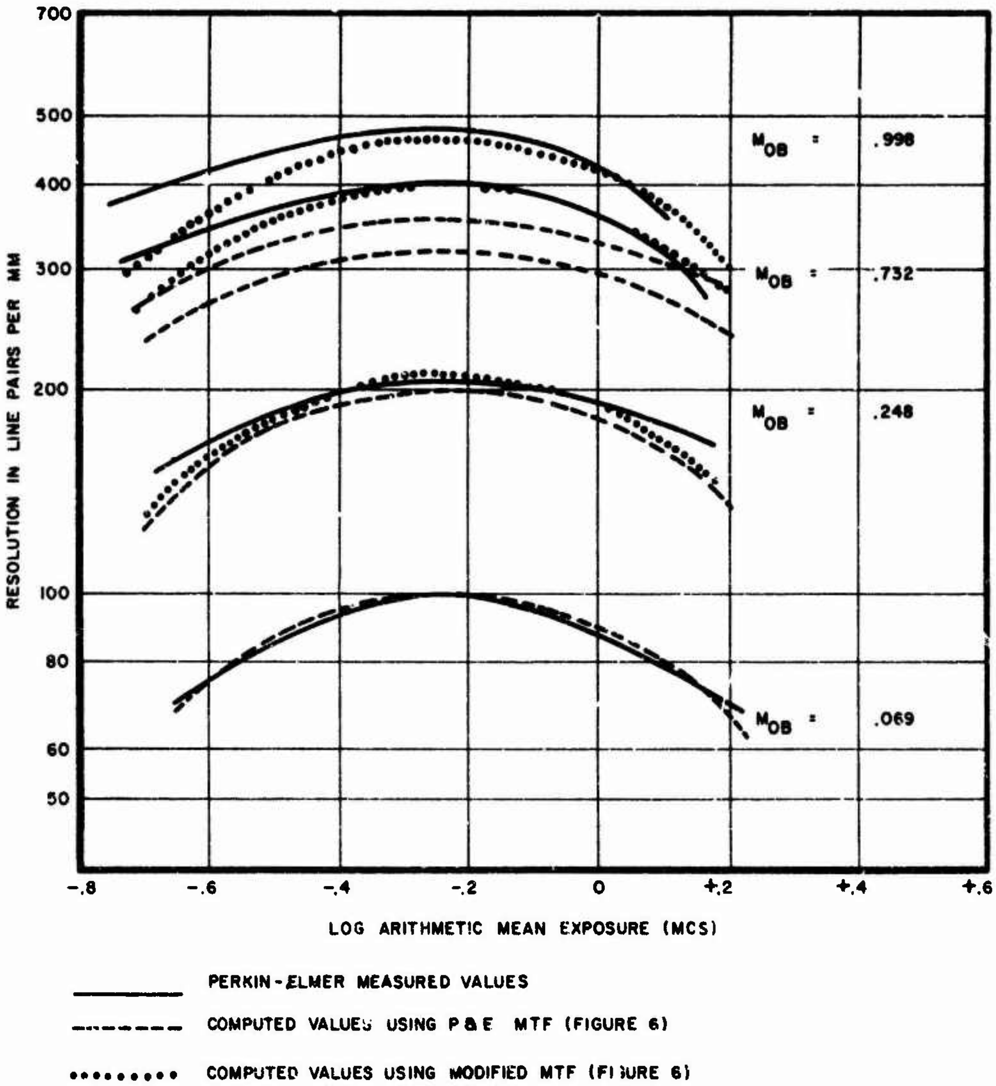

Figure 7. Resolution vs Exposure Curves EK 3404
(Computed and Measured)

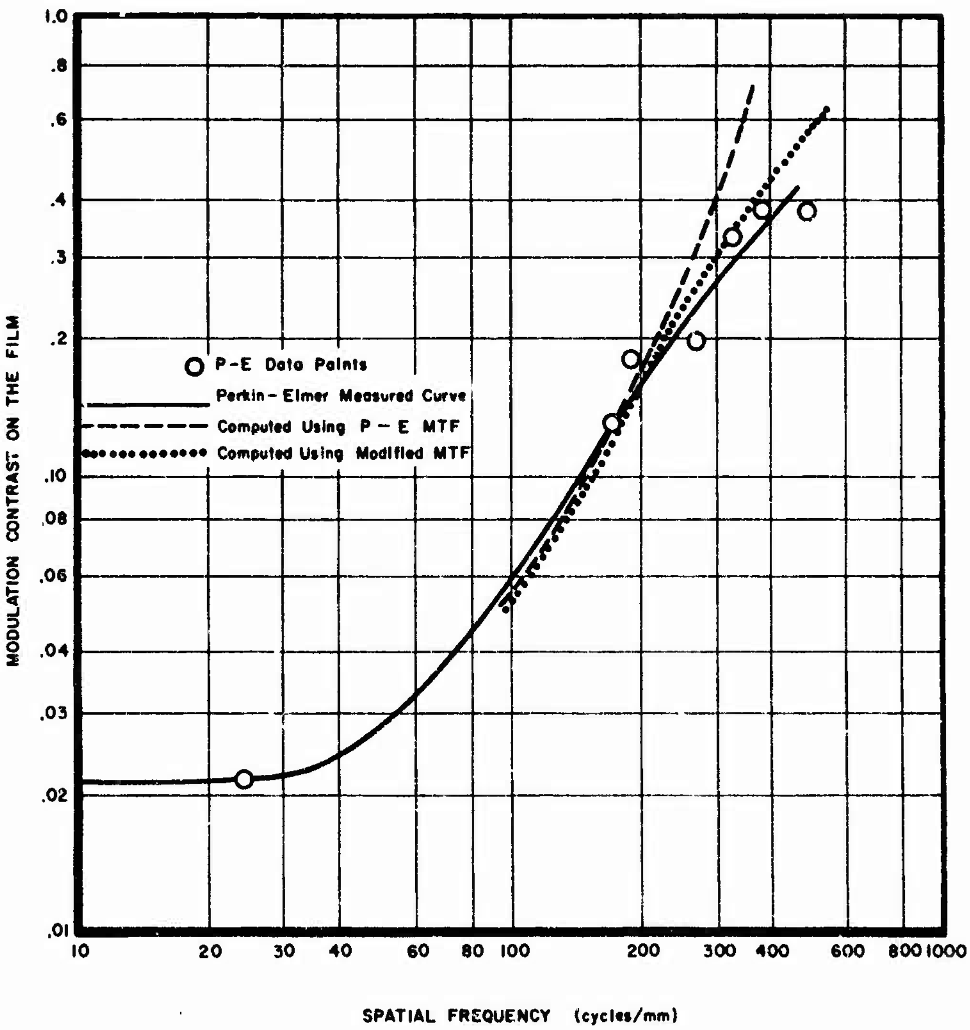

Figure 8. Three-Bar Target Modulation Detectability EK 3404 (Computed and Measured)

SECTION VI

DETECTION RANGE

To illustrate how useful these analytic techniques are, consider the well known problem of detection range.

Since angular resolution equals object size divided by range, Equation (29) can be rewritten in the form

$$\left[DR\right] = \frac{S\, M_{OB}\, \phi_{S-\gamma} \left(\bar{\rho}\, H_S\, \tau_T\, t\, n\, \hat{Q}_M\right)^{1/2} D}{k\; 1.414} \qquad (32)$$

where

[DR]	=	Detection Range Limit in meters
S	=	Object Size (minimum dimension) in meters
M_{OB}	=	Contrast (modulation) of object (target) and its background
$\phi_{S-\gamma}$	=	Target response function for total system less the "gamma function"
$\bar{\rho}$	=	Arithmetic mean reflectance of object (target) and its background
H_S	=	Irradiance on scene in watts per square meter
τ_T	=	Total transmittance of system from object to detector
t	=	Integration time in second
n	=	Number of photons per joule of radiant energy used
$\hat{Q}_M$	=	Detective Quantum Efficiency
D	=	Diameter of optical collector in meters
k	=	Signal to Noise threshold (approximately 3 for detecting isolated objects with low length to width ratio)

Thus we see that the range at which an object can be detected is directly proportional to the size and contrast (modulation) of the object and its background, the degree to which this contrast will be reduced by all contrast reducing effects of the total system (except the gamma function), and the diameter of the collector. This detection range is also proportional to the square root of the arithmetic mean reflectance of target and background, irradiance on the scene, total transmittance of the system integration time, number of photons per unit of radiant energy involved, and detective quantum efficiency. [DR] is inversely proportional to the S/N threshold. In the case of detection (where one is discriminating an isolated object or point k is approximately 3 in an electro-optic (EO) system with dynamic noise). In applying this and other equations of this type it must be remembered that $\phi_{S-\gamma}$ is a function of range and other quantities are functions of each other as well as wave length (λ).

thus

$$M_{OB} = f\left(\bar{\rho}, \rho_M, \rho_m, \lambda\right)$$

$$\phi_{S-\gamma} = f\left(M_{OB}, \left[DR\right], \bar{\rho}, H_S, \tau_T, S, \lambda\right)$$

$$H_S = f(\lambda)$$

$$\tau_T = f\left(\left[DR\right], \lambda\right)$$

$$n = f(\lambda)$$

$$\hat{Q}_M = f\left(M_{OB}, \phi_{S-\gamma}, \bar{H}_d, \lambda\right)$$

or

$$\hat{Q} = \hat{Q}_{M_O} = f\left(\bar{H}_d, \lambda\right) \text{ as } M_{OB}\,\phi_{S-\gamma} \longrightarrow 0$$

$$\bar{H}_d = f\left(H_S, \bar{\rho}, F, D, \tau_T, V', N_A, \text{ etc}\right)$$

Such an equation as Equation (32) with this type interdependency can be solved by suitable computer software.

SECTION VII

RECOGNITION RANGE

The problem of recognizing the shape of an object has been shown to be related to resolving power. Most simple shapes can be said to be recognizable if the object (the minimum dimension) equals approximately 4** resolved line pairs. Equation (32) becomes for recognition range

$$\left[RR\right] = \frac{S\ M_{OB}\ \phi_{S-\gamma}\left(\bar{\rho}\ H_S\ \tau_T\ tn\ \hat{Q}_M\right)^{1/2} D}{8\ k\ 1.414} \qquad (33)$$

where k approximately = 1.2 (dynamic noise). Since k in Equation (32) = approximately 3 detection [DR] is equal to approximately 3.2 times the recognition range [RR]. This is more nearly true for those cases where $\phi_{S-\gamma}$ is not very dependent on range and the final contrast at the detector is low. In the case where there is considerable backscatter and particularly when the target to background contrast is high, detection range can be much greater than 3 times the recognition range. Each case must be evaluated separately.

* see Equation (25)

** John Johnson, Ft Belvoir, Virginia, Oct 1958

SECTION VIII

IDENTIFICATION

Since identification often depends upon many subjective clues and apriori knowledge about the scene being viewed, an equation for identification range is not considered advisable.

Equations (32) and (33) can be very useful tools in the analysis of any Electro-Optical System and when one considers the spectral dependence of the many terms (see Section VI) it can become more useful.

SECTION IX

SPECTRAL DEPENDENCE

In Equation (32) let $f(\lambda)$ equal $M_{OB}\ \phi_{S-\gamma}\ (\bar{\rho}\ H_S\ \tau_T\ nQ)^{1/2}$ since all these terms are functions of wavelength λ. To evaluate for a given size target S, lens diameter D and integration time t we must integrate $f(\lambda)$ over the wavelength interval being employed by the sensor, thus

$$F(\lambda) = \int_{\lambda_1}^{\lambda_2} f(\lambda)\, d\lambda \tag{34}$$

The following is a graphical portrayal of this procedure with comments on possible optimization procedures.

Compute first M_{OB} as a function of λ given $\rho_0(\lambda)$ as spectral reflectivity of object and $\rho_B(\lambda)$ as spectral reflectivity of background. See Figure 9.

Spectral $M_{OB}\ (\lambda)$ is found from

$$M_{OB}(\lambda) = \frac{|\rho_O(\lambda) - \rho_B(\lambda)|}{\rho_O(\lambda) + \rho_B(\lambda)}$$

which considers all M_{OB} as though they were positive when, in fact, the image polarity reverses at the cross-over points of $\rho_0(\lambda)$ and $\rho_B(\lambda)$. Since it is possible to electronically or photographically reverse this polarity in the display, and in an efficient system with suitably selected spectral filters select the wavelength intervals between cross-over points and obtain an additive effect, we will keep track of this polarity. (See Figure 10 for $M_{OB} - f(\lambda)$.

In Figure 10, the square root of the arithmetic mean reflectivity of object and background $\bar{\rho}^{\ 1/2}$ is also plotted as a function of wavelength $\bar{\rho} = \frac{\rho_0 + \rho_B}{2}$ Multiplying $\bar{\rho}^{\ 1/2}$ by M_{OB} at each wavelength we obtain $M_{OB}\bar{\rho}^{\ 1/2}$ as a function of λ in Figure 11.

$$R_{lim} = SDt^{1/2}\int_{\lambda_1}^{\lambda_2} f(\lambda)\,d\lambda\ 1.414 \times 10^{-2} \qquad f(\lambda) = M_{OB}(\bar{\rho}\, H_S n \tau_T Q)^{1/2}\phi_{S-\gamma}$$

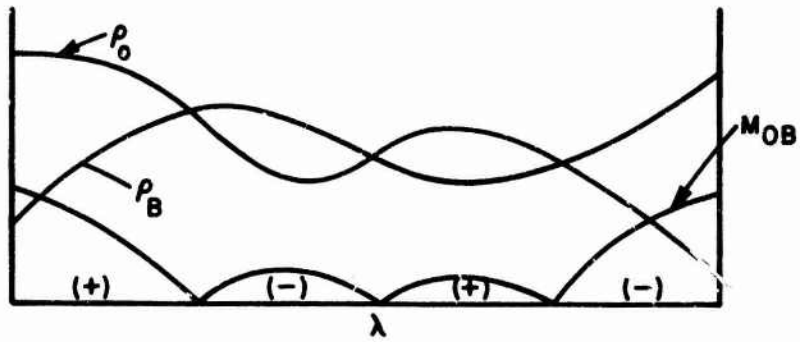

Figure 9. Reflectivity and Modulation Contrast as Function of Wavelength

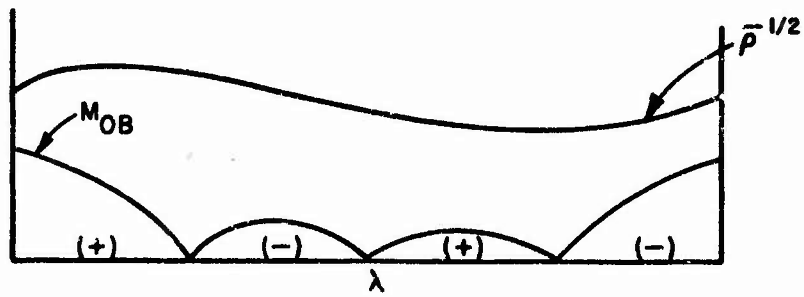

Figure 10. Square Root of Mean Reflectance and Modulation Contrast Function in Figure 9

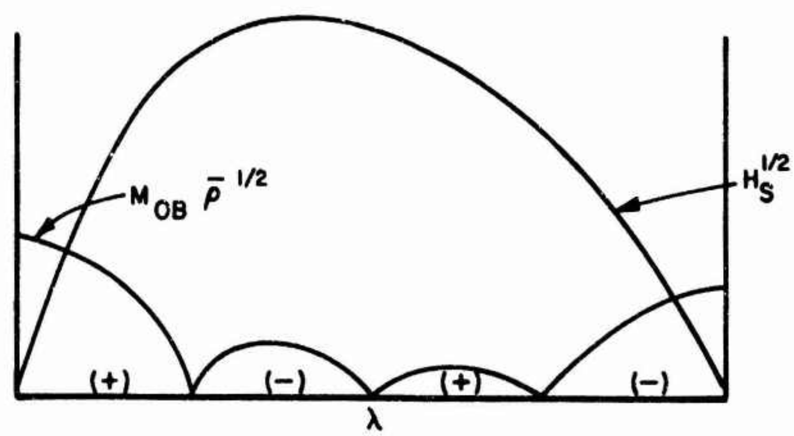

Figure 11. Square Root of Scene Irradiance and Total Product in Figure 10

Also in Figure 11, we plot the square root of the irradiance on the scene $H_S^{1/2}$ as a function of λ and multiply by $M_{OB}\bar{\rho}^{1/2}$ to obtain $M_{OB}(\bar{\rho}H_S)^{1/2}$ as a function of λ in Figure 12.

Figure 12 also gives $n^{1/2} = f(\lambda)$ where n is the number of photons per joule. Figure 13 illustrates this product along with $\tau_T^{1/2} = f(\lambda)$ where τ_T is the total transmission of the system including atmosphere, optics, filters, etc.

The product of the two functions in Figure 13 are plotted in Figure 14 as $M_{OB}(\bar{\rho}\, H_S\, n\, \tau_T)^{1/2}$ and a typical $(\hat{Q})^{1/2} = f(\lambda)$ is also illustrated. For purposes of determining the limiting detection range [DR], the modulation contrast out (M_{OUT}) will be low (at the threshold of the discriminator). The (S/N_{out}) is also low (at the threshold of the discriminator) and therefore we can use the $\hat{Q}$ for low contrast, which is the limiting case of $\hat{Q}_M = Q$ as $M \to 0$. We also select $\hat{Q}$ for optimum exposure ($H_d t$) or optimum irradiance at the detector (See Figure: 1a, 5a and Equation (20)). This will result in adjusting either t the integration time, or, if this is fixed by the sensor design, the effective f# of the system which can be done by adjusting the effective lens diameter or focal length.

$M_{OB}\left(\bar{\rho}\, H_S\, n\, \tau_T \hat{Q}\right)^{1/2} = f(\lambda)$ is illustrated in Figure 15 along

with $\phi_{S-\gamma} = f(\lambda)$

$$\phi_{S-\gamma} = \phi_T \cdot \phi'_{NA} \cdot \phi'_V$$

where

ϕ'_{NA} = modulation contrast reduction function due to the atmosphere (not spatial frequency dependent but is λ dependent).

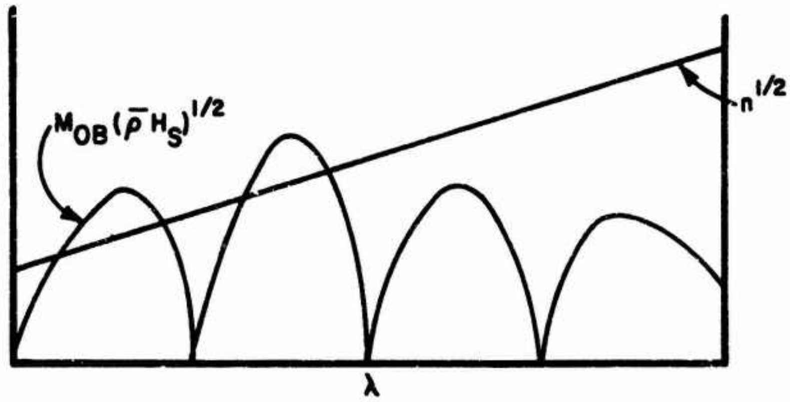

Figure 12. Square Root of Number of Photons per Joule and Total Product in Figure 11

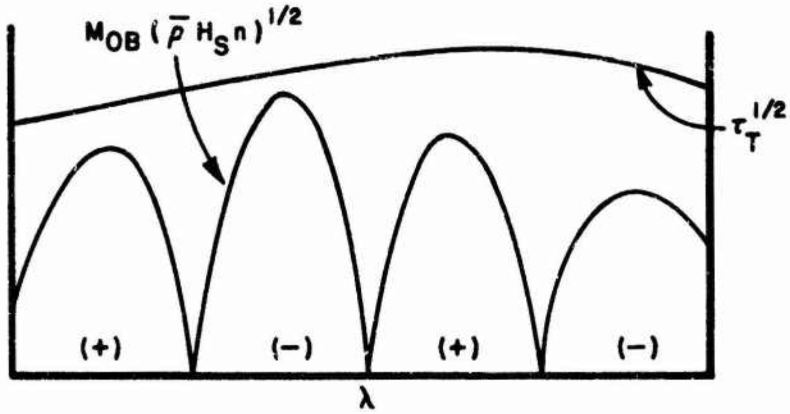

Figure 13. Square Root of Total System Transmittance and Total Product in Figure 12

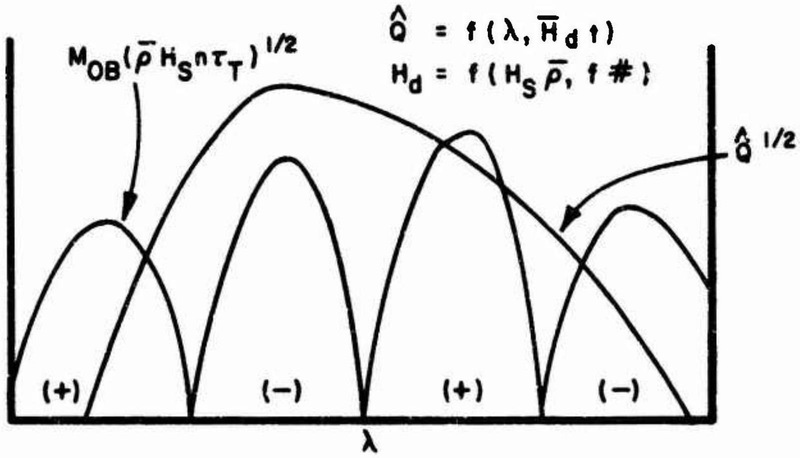

Figure 14. Square Root of Detective Quantum Efficiency and Total Product in Figure 13

ϕ_V' = modulation contrast reduction functi[illegible]e to veiling glare (not spatial frequency [illegible]endent but is λ dependent).

ϕ_T = spatial frequency dependent target response function of the system and includes spread function of the optical system which is λ dependent (due to chromatic aberrations and color filters) and includes lenses, atmospheric turbulence, filters, etc. It also includes spread functions resulting from image smear and is not λ dependent. It is also a function of t and storage surface lag in some systems. The spread function of the detector/display subsystem is also included and sometimes, due to selective spectral spread of irradiance in the detector, it can be λ dependent to a lesser degree. This function includes all point spread functions from detector through the display such as light spread in detector, spread due to readout mechanisms for the detector (physical and electronic) various aperture response functions such as scanning apertures and electron beams as well as spread functions in the display. It is always determined in terms of the effective spread function within or at the detector by removing the effect of the nonlinear Detector Display Characteristic Curve.

$$\phi_T = \frac{M_{OUT}(E_T * S_S)}{M_{IN}(E_T)}$$

Where E_T is energy distribution of target and S_S is spread function of system.

Since ϕ_T is spatial frequency dependent, the proper value is determined by the angle subtended by S (object size). It is therefore, a function of [DR] which is the function we are determining. ϕ_{NA} also is a function of [DR]. A reiterative computational technique to maximize R can be used or instead of computing [DR] as in Equation (32) with k=3, we can compute $(S/N)_{out}$ for a series of fixed object sizes S at different ranges. This will give $(S/N)_{out}$ = f(R) with S as a parameter. At $(S/N)_{out}$ = 3 we can determine the function R = f(S).

Since we are using the optimum value of $\hat{Q}$, we have as a result determined t if it is not fixed by the system design and we can therefore determine the spread function due to image motion for a given V/H.

The final function $M_{OB}\ (\bar{\rho}\ H_S\ n\ \tau_T\ \hat{Q})^{1/2}\ \phi_{S-\gamma} = f(\lambda)$ is illustrated in Figure 16. The optimum optical filtering or wavelength interval for integration is immediately apparent. If one wishes to use two wavelength intervals (i.e., an optical filter with two transmission bands) the proper wavelength intervals are apparent (use only positive or only negative polarity intervals between cross over points). Another possibility which could use more of the available photons would be to use all four bands with two data channels and reverse the polarity of one channel. Efficient filters are required to obtain a significant advantage from this filtering and data processing technique. Also, if two separate optical systems or sensor systems with a single display are required instead of a time sharing system with changeable filters, it will probably be more effective to just use a larger lens and one channel for the same total system weight and less complexity.

At high levels of scene irradiance and scene reflectivity where the optical system must be used at smaller lens diameter (large f#) to prevent detector/display saturation, a more efficient use of the available photons can be achieved by using a less sensitive detector/display, yet one having the same D.Q.E. This type of detector can yield a "high gamma" without too much RMS noise out.

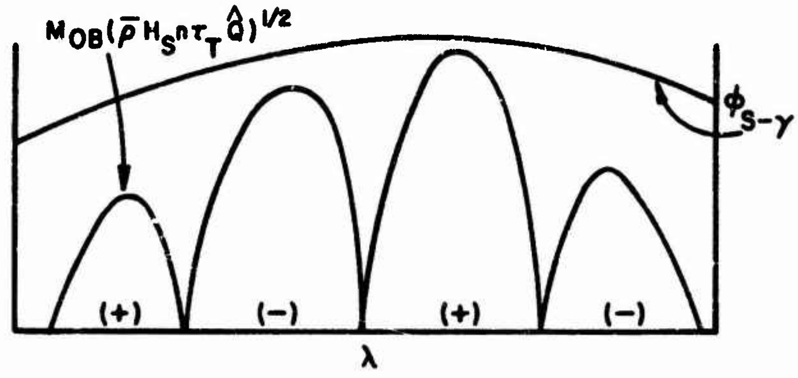

Figure 15. Target Response Function and Total Product of Figure 14

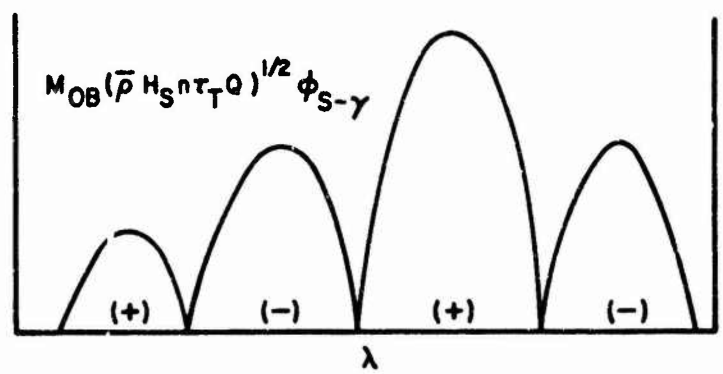

Figure 16. Final Product of all Functions as a Function of Wavelength

SECTION X

CONCLUSIONS AND RECOMMENDATIONS

For many purposes, such as; evaluating, comparing and ranking systems, predicting system performance both in the design stage and under operational conditions, and understanding the limitations and controlling factors of an imaging system, it is not necessary to consider in detail all the parameters of individual components of the system. For the designer of individual components or for one making tradeoff studies involved in selection of components or parameters it is well recognized that specific details such as MTF/OTF, individual sources and types of noise, the noise spectrum and problems associated with sampling theory are important.

The relative importance of the significant aspects of system parameters (in both its components and conditions of use) such as MTF/OTF or spread function, D.Q.E., noise, resolution, gain, contrast, contrast reducing effects, available energy, wavelength dependence, etc. become more apparent when viewed from the point of view of the general equation:

$$\frac{R^2 (S/N)^2_{OUT}}{M^2_{WIN}} = \frac{\bar{H}_d \, t \, n \, \hat{Q} \times 10^{-6}}{2}$$

The above equation has been shown to be general enough in its basic physics point of view that it can be made applicable to all types of noncoherent image forming systems such as Photography, T.V., E.O. line scan systems, direct view image intensifiers and image converters, image data links and re-imaging systems, IR line scan systems, forward looking IR(FLIR), etc.

It is recommended that the approach outlined in this report be taken when one is comparing sensor systems of different types.

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